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Localized micromagnetic perturbation of domain walls in magnetite using a magnetic force microscope

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Magnetic force microscope (MFM) profiles of domain walls (DWs) in magnetite were measured using commercially available MFM tips. Opposite polarity profiles of a single DW segment were obtained by magnetizing the MFM tip in opposite directions perpendicular to the sample surface. During a measurement, the field of the tip locally magnetized the DW, resulting in a more attractive tip-sample interaction. The difference between opposite polarity DW profiles provided a qualitative measurement of the reversible changes in DW structure due to the localized field of the MFM tip. © *1996 American Institute of Physics.* [S0003-6951(96)02148-1]

The use of the magnetic force microscope (MFM)[1,2] as a high resolution probe of micromagnetic structure relies on the understanding of the role of the MFM tip field in the measurements.[3] Although most analyses of MFM data have been based on the assumption that the MFM response is linear in the sample field, i.e., that no alteration of the sample or tip magnetizations occurred while imaging, numerous investigations on magnetically soft samples have demonstrated significant perturbation of the micromagnetic structure by the tip field.[4–8] These works led to the development of MFM tips with lower stray fields[9] and experiments which exploited the localized MFM tip field.[10,11]

The present work isolates the influence of the local magnetic field of the MFM tip on 180° domain walls (DWs) in magnetite (Fe_3O_4) single crystals. In general, the MFM tip field will reorientate the sample spins resulting in a more attractive interaction between the tip and sample. We measured the modification of a DW from profiles made with opposite tip magnetization perpendicular to the surface. The magnitude of the reorientation should be proportional to the local susceptibility. The first MFM study of Fe_3O_4 not only neglected surface topography effects, but also tip field-induced alteration of the sample structure.[12] Our later work considered these effects, but did not include any nonlinear interactions in the analysis.[13]

The Fe_3O_4 single crystal samples we investigated were bulk samples of thickness on the order of 1 mm. The samples were grown in the [110] direction[14] and then cut and polished parallel to a {110} plane.[15] Fe_3O_4, like Ni, is a cubic crystal with $K_1<0$ and $\langle 111\rangle$ easy axes. The {110} contain two $\langle 111\rangle$ axes allowing observation of domain structures which replicate the interior domain structures with 180°, 109°, and 71° DWs.[16] A typical MFM image of an area containing all three DW types is shown in Fig. 1(a).

Micromagnetic calculations predict the structure of 180° DWs intersecting the surface of a thick film or bulk sample to rotate from Bloch-like in the bulk to a Néel-like ''cap'' to reduce the surface magnetostatic energy.[17,18] The result of a 2D micromagnetic simulation of a 180° DW in Fe_3O_4 is shown in Fig. 1(b).[19] Figure 1(c) shows a cartoon of a simple model of this DW structure in which the bulk Bloch DW is represented by a magnetic dipole oriented perpendicular to the surface. The Néel cap is represented by a dipole in the surface plane perpendicular to the bulk (Bloch) dipole.[6]

A multimode™ MFM and Nanoscope III from Digital Instruments operated in tapping™/liftmode™ was used to obtain surface topography and magnetic force gradient profiles separately.[20,21] Commercially available MFM probes were used for this work.[22] Hysteresis loops of the magnetically active volume of these probes were square with coercivity of approximately 400 Oe.[23]

Multiple topographic and magnetic force gradient profiles were measured along a single line above the central region of a long 180° DW segment. In the limit that the MFM tip can be treated as a fixed point dipole, the magnetic force gradient is proportional to $\partial^2\mathbf{B}/\partial z^2$ where $\mathbf{B}$ is the sample stray field.[24] It was experimentally verified that the magnetic force gradient profiles were a measure of the z component, $\partial^2 B_z/\partial z^2$.[25,26] Since $\partial^2 B_z/\partial z^2$ is symmetric across the DW for the bulk vertical dipole, and antisymmetric for the surface horizontal dipole, the addition of both contributions results in an asymmetric MFM response profile.[13] The profiles measured in this work were asymmetric regardless of the tip magnetization.

Profiles of a DW will be defined as repulsive or attractive according to the sign of the magnetostatic interaction of each measurement. An attractive(repulsive) profile was measured with the tip magnetized parallel(anti-parallel) to the bulk Bloch DW magnetization. Repeatable differences between these two types of profiles were indicative of reversible modification of the DW micromagnetic structure.[27]

Cartoons of DW structures altered by the MFM tip field are illustrated in Figs. 1(d) and 1(e). In the repulsive case, the spin components parallel to the vertical Bloch wall are decreased and the in-plane Néel cap components are enhanced.

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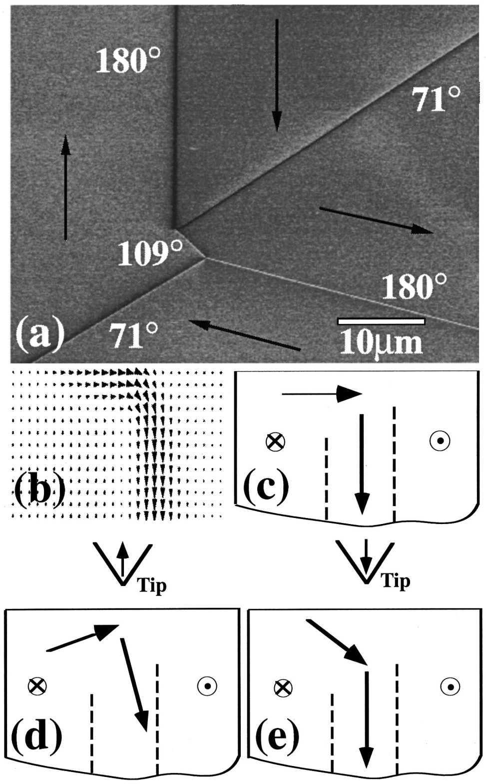

FIG. 1. (a) A liftmode MFM image of an area of a Fe_3O_4 single crystal containing three types of DWs: 180°, 109°, and 71°. The bold arrows indicate the direction of magnetization in the bulk of each domain. (b) Results of a 2D micromagnetic simulation of a 180° DW in Fe_3O_4. This cross section of the sample shows that the magnetization is out of the page on the right of the wall and into the page on the left. The vertical arrows in the sample interior indicate that the DW is a Bloch DW in this region, but near the surface, the spins in the DW gradually rotate into the surface plane to form a Néel-like DW portion referred to as a Néel cap. (Figure courtesy of S. Xu and D. Dunlop.) (c) A cartoon of the 180° DW structure in (b). The bulk Bloch DW is represented by a perpendicular magnetic dipole with the top pole about one Bloch DW width below the surface. The surface Néel cap is represented by an in-plane dipole perpendicular to the Bloch DW plane. (d) A schematic of the *repulsive* MFM measurement of this DW structure in which the tip is magnetized antiparallel to the bulk dipole moment. In this case, the tip field enhances the Néel cap. (e) A schematic of the *attractive* DW measurement for which the tip is magnetized parallel to the bulk dipole moment. The tip field reduces the Néel cap in this case.

In the attractive case, the opposite occurs so that the Néel cap is less pronounced relative to the symmetric Bloch contribution. Experimental evidence supporting this general behavior is shown in Fig. 2. The profiles, (a) and (b), in Fig. 2 are *both* asymmetric, but their asymmetries are markedly different from each other.[28] The influence of the tip field produced a more antisymmetric profile in the repulsive case and a more symmetric profile in the attractive case. We observed similar behavior in profiles measured above opposite polarity segments of subdivided 180° DWs made with fixed MFM tip magnetization.[29]

A way to measure the alteration of the DW is demonstrated in Fig. 2(c) in which the repulsive profile [Fig. 2(a)] was inverted and superimposed on the attractive profile [Fig. 2(b)].[30] Note that the unperturbed DW profile should lie between these two profiles. The difference, $b-(-a)$, between these two profiles [shaded in Fig. 2(c)] has been plotted in Fig. 2(d), giving the combined modifications of the DW from both profiles.

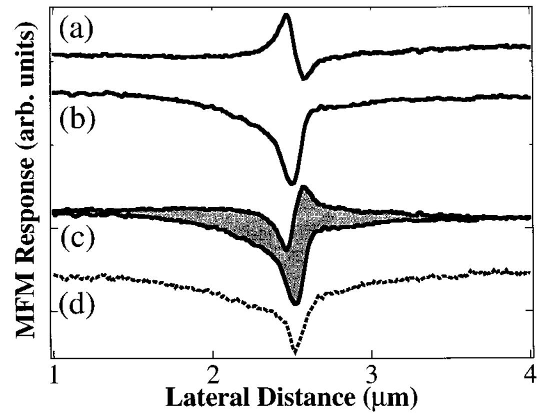

FIG. 2. Two MFM response profiles, (a) and (b), measured above the same 180° DW using the same MFM tip at a lift height of 30 nm. Profile (a) was measured with the tip magnetization antiparallel to the bulk Bloch DW magnetization, i.e., the *repulsive* case. For profile (b), the measurement was *attractive* with the tip magnetization parallel to the bulk Bloch DW. In (c), profile (a) was inverted and superimposed on profile (b). The difference between them has been shaded. Profile (d) is the difference profile, $b-(-a)$ which shows the additional, attractive MFM response due to the effect of the tip field on the DW structure.

The deformation of the DW magnetization by the tip field should decrease with tip-sample separation. Figure 3 demonstrates this with profiles of a 180° DW measured in the two tip states as a function of lift height. Repulsive and attractive profiles are plotted for lift heights of 15, 50, and 200 nm, respectively. At 15 and 50 nm, the symmetries of the DW profiles in the two cases are very different from each other, the repulsive case being more antisymmetric. As the lift height increases and the magnitude of the tip field at the position of the DW decays, the opposite polarity profile symmetries become more alike. The difference profile for each lift height is shown in Fig. 3(c). Although significantly decreased, the difference was still visible 200 nm above the sample surface. Hence, to avoid nonlinear, inductive imaging, considerable lateral resolution would have to be forfeited.[31]

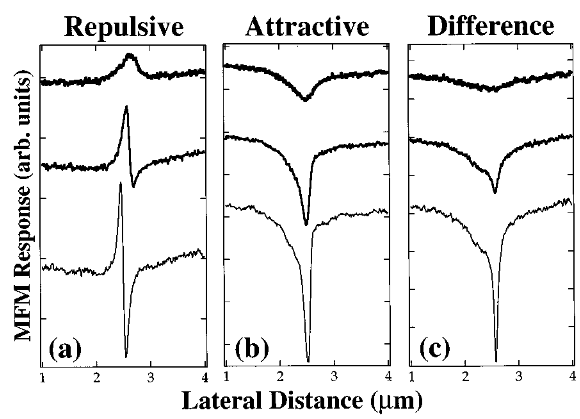

FIG. 3. MFM profiles measured at various lift heights above a 180° DW with the same MFM tip. (a) Profiles measured repulsively as in Fig. 2(a). (b) Profiles measured attractively as in Fig. 2(b). Each profile is an average of 20 line scans measured above the same spatial location, perpendicular to the wall. (c) Difference profiles found by subtracting the inverted, repulsive profile from the attractive profile for each lift height as in Fig. 2(d). The top, middle, and bottom curves were measured at lift heights of 200, 50, and 15 nm, respectively.

In conclusion, we studied the effects of the localized magnetic field of MFM tips on 180° DWs in single crystal Fe_3O_4. The difference between opposite polarity profiles, i.e., profiles measured with opposite tip magnetization in the $\hat{z}$ direction, gave a qualitative measure of the reversible tip-sample interactions. For Fe_3O_4, it was verified that the z component of the DW field is asymmetric across the DW which is consistent with the existence of Néel caps on the DWs. This MFM measurement procedure could be applied in general to studies of micromagnetic objects in relatively soft magnetic materials as a way of isolating reversible tip field effects and constraining the effects of the nonlinear tip-sample interactions.

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[26] For the profile measurements, the cantilever was parallel to the wall so that the major in-plane component of the tip magnetization (imposed by the tilt of the cantilever) was parallel to the wall. The sample was rotated 180° under the tip to effectively reverse only the x component (perpendicular to the wall) of the tip magnetization. Profiles measured with opposite tip magnetization components in the x direction were identical, indicating that the profile measurement was due mainly to tip magnetization in the z direction.
[27] Because the repulsive and attractive measurements were made at slightly different equilibrium heights above a DW, it was verified that the change in Q value between the two heights did not contribute to the difference in the two types of DW profiles. An experiment using a standard hard disk sample showed that profiles of opposite polarity bits had identical symmetries and signal to noise ratios (S/N) when measured at heights where the S/N was comparable to that above the Fe_3O_4 DWs. This also verified that differences between opposite polarity profiles were not due to partial switching of the tip magnetization.
[28] These profiles are the average of 20 line scans measured successively while alternating scan direction above the same line. Profiles scanned in opposite directions were identical.
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[30] Definition of the DW center was different for each type of profile measurement; however, care was taken to remain over the same area of the DW before and after the tip magnetization was reversed using topographical features. Also as profiles were measured repeatedly over the same line, a measure of the lateral drift with time was made and accounted for in aligning the two profiles for calculation of the difference profile.
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